Shaping Planetary Nebulae and Related Objects

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ABSTRACT

I review some open questions and other aspects concerning the shaping of planetary nebulae (PNs) and related objects. I attribute the non-spherical structures of PNs to binary companions, stellar or substellar. I emphasize the role of jets (or collimated fast wind: CFW) blown by an accreting stellar companion in shaping bipolar PNs and some related objects, and discuss the limited role of magnetic fields. I speculate that some stars which are leaving the asymptotic giant branch, i.e., becoming hotter, possess long-term (10-1000 years) oscillations; these may be related to semi-periodic concentric rings. I end with a list of objects whose shaping is related to the shaping processes of PNs, from young stellar objects to clusters of galaxies.

1. Introduction

This paper addresses some of the following open questions related to the shaping of planetary nebulae (PNs), with a number of comparisons to related objects.

1. Why and when does mass loss rate from asymptotic giant branch (AGB) progenitors of PNs become non-spherical? Many AGB stars lose mass in a spherical geometry, while most PNs are axisymmetric, or point symmetric. At the end of the AGB the mass loss geometry must change to become non-spherical. I address this question, and show that the binary model for the shaping of PNs can account for it, in section 2.

2. What is the connection of multiple semi-periodic concentric shells (arcs; rings; termed M-arcs) to the previous question? These are thought to be concentric (more or less) semiperiodic shells; some shells are complete while others are not. Reviews of the arc and ring properties are given by Hrivnak, Kwok, & Su (2001), Kwok, Su, & Stoesz (2001), Su (2004), and Corradi et al. (2004). I address this question in section 4.

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3. When does a star in the “right” initial mass range form a PN? I will not address this issue directly here, but it is important when comparing theory with observations, e.g., in population synthesis studies. Soker & Rappaport (2000) discuss this issue. In particular, some stars will not form PNs: either they lose most or all of their envelope before reaching the upper AGB, or their mass loss rate while terminating the AGB is too low, and the PN will be too faint to be detected. This issue is related to questions raised be De Marco (2004) on the number of PNs with binary central stars.

4. What are the roles of jets in shaping PNs? If jets are not well collimated, I term them CFW, for collimated fast wind. In this respect, I will present the view that most, or even all, jets in PNs are blown by a binary companion–or even by a tertiary star. I elaborate on this question in relation to jets in clusters of galaxies in section 5.

5. What is the role of axisymmetric mass loss from the AGB stellar progenitor? Models for enhanced equatorial mass loss rate include fast rotating AGB stars, which were spun-up by companions (Soker 1997), and effects of magnetic fields. I will mention the presence of magnetic fields on the surface of AGB stars, and present my view that even when magnetic fields are detected, they are not likely to play a global (as opposed to local) dynamical role in the mass loss process from the AGB star. In section 3 I will try to clarify some confusion related to the roles of magnetic fields in shaping PNs.

Although this paper is basically a review following the Asymmetrical Planetary Nebulae III (APN3) meeting, it contains some new ideas as well. It doesn’t of course address all relevant questions, and doesn’t cite many papers; many of these can be found in papers already cited here. Note in particular the recent review by Balick & Frank (2002), which contains many references and relevant discussions, as do many papers in the Proceedings of APN3 (I hope all will be posted on astro-ph).

2. Basic Types of Binary Interaction

I distinguish between four basic types of interaction with stellar or substellar companions. Two of these lead to the formation of axisymmetrical PNs.

1. No interaction. There is no companion to the AGB progenitor, or the companion has too little mass and/or the orbital separation is too large. In that case a spherical PN is expected, and/or the mass loss rate stays low, and no observable PN ever emerges.

2. A very-wide companion. The companion does not influence the mass loss process because the orbital separation is too large, $a \gtrsim 100$ AU. However, the companion is

close enough, $a \lesssim 10^4$ AU, and massive enough, i.e., a stellar companion, such that it causes a departure from axisymmetry (see Soker & Rappaport 2001 for detailed study of this process, and references therein; Classification of PNs according to their departure from axisymmetry is reviewed by Bobrowsky 2004).

3. Shaping without disturbing the AGB progenitor. In this type of interaction the companion deflects the AGB wind, but it doesn't influence the AGB progenitor itself. In the main process (Soker 2001a) the compact companion accretes from the AGB wind such that an accretion disk is formed, resulting in two jets (or a CFW). Soker (2001a) finds that $\sim 5 - 20\%$ of all PNs are formed by this process.

4. Shaping by disturbing the AGB progenitor. This type of interaction includes tidal interaction, Roche lobe over flow (RLOF), and common envelope. RLOF and tidal interaction (RLOF implies tidal interaction, but tidal interaction can occur without RLOF; Soker 2002c) are likely to lead to the formation of jets, and the formation of a bipolar PN with a narrow waist between the two lobes or bubbles (Soker & Rappaport 2000). During the common envelope phase jets are not likely to be blown, but the companion may blow jets prior to entering the CE or immediately after. Common envelope models include substellar companions (planets and brown dwarfs) as well.

The different types of interaction, the nature of the companion, and more on their relation to the shaping of PNs are in some of my earlier papers (e.g., Soker 1997; 1998; 2002c; Soker & Rappaport 2000). Note that a very-wide companion can exists together with a closer companion. This is indeed the case in many PNs showing departure from axisymmetry or from point-symmetry (Bobrowsky 2004).

In the binary model for shaping PNs, i.e., in the last two basic types of interaction, it is expected that the shaping mainly occurs as the progenitor is about to leave the AGB, and during the early post-AGB phase (for related phenomenon see the discussion of subdwarf B binaries in section 6). When the companion is at a large orbital separation (interaction type 3), the formation of a stable accretion disk, and presumably the formation of a CFW (or two jets), requires the AGB wind to be intensive and slow (Soker 2001a). Practically, for a significant fraction of binary systems to blow jets ($\gtrsim 10\%$ of initial binary systems), the AGB mass loss rate should be $\dot{M}_1 \gtrsim 10^{-6} M_\odot$ yr^{-1} for a wind speed of $v_w \sim 7$ km s^{-1}, and $\dot{M}_1 \gtrsim 10^{-5} M_\odot$ yr^{-1} for a wind speed of $v_w \sim 11$ km s^{-1} (Soker 2001a). As mass loss rate increases in the range $\gtrsim 2 \times 10^{-6} M_\odot$ yr^{-1}, the AGB wind speed decreases (Elitzur, Ivezic & Vinkovic 2002). Therefore, this condition, of very high mass loss rate and a slow wind, is met only during the so-called superwind phase of the AGB, when mass loss rate is very high and wind speed is low. Huggins et al. (2003) find the flow structure in the bipolar proto-PN

He 3-1475 to support such scenarios, i.e., where enhanced mass loss by the central star leads to ejection of two jets.

In the second basic type of interaction that leads to the formation of axisymmetrical PNs (type 4 interaction above), the companion substantially spins-up the AGB envelope, in particular during the strong tidal interaction phase, prior to the onset of RLOF and common envelope. Most of the spin-up, i.e., deposition of orbital angular momentum to the AGB envelope, occurs during a very short time (Soker 1995). This is likely to enhance mass loss rate. Therefore, this type of interaction both increases the mass loss rate and changes it to axisymmetric, rather than spherical. The high mass loss rate implies that the AGB progenitor is about to leave the AGB shortly.

One conclusion from the correlation between AGB high mass loss rate and the transition to axisymmetry, as observed and as expected in the binary model, is that most spherical PNs will not show signatures of superwind. This is indeed the case when one carefully defines spherical PNs (Soker 2002a, §2.2).

3. Comments on the Role of Magnetic Fields

The previous section, which clarified some aspects of binary interaction and the shaping of PNs, would not be complete without clarification of some aspects of magnetic fields.

3.1. The source of magnetic fields

There are now clear indications of magnetic fields in PNs and around AGB stars. The strongest indication comes from polarized maser emission (e.g., Kemball & Diamond 1997; Zijlstra et al. 1989; Miranda et al. 2001a; Vlemmings, Diamond, & van Langevelde 2002; Indra 2004). In many cases the *local* magnetic pressure inferred from the maser polarization is about equal to, or even larger than, the thermal pressure of the gas. Some papers claim that the strong magnetic fields indicate that magnetic fields globally shape PNs. I think that this conclusion is hardly justified. Instead, I (Soker 2002d) argue for magnetic fields with small coherence lengths, which result from stellar magnetic spots or from jets blown by an accreting companion; the magnetic field does not play a global role in shaping the circumstellar envelope. In the solar wind, in general, magnetic pressure exceeds thermal pressure only in magnetic clouds (e.g., Yurchyshyn et al. 2001), which are formed by impulsive mass loss events from the sun. In Soker & Kastner (2003) we suggest that the maser spots with strong magnetic fields which are observed around some AGB stars are similar in nature

to the magnetic clouds in the solar wind, in that they represent local enhancements of the magnetic field. In related papers, Dorch & Freytag (2002) discuss local dynamo in Betelgeuse, and in Soker (2002e) I discuss enhanced magnetic activity of the cool companion in symbiotic systems.

To summarize this subsection, I expect the global magnetic pressure in the wind of AGB stars to be much below the thermal pressure, as winds from AGB stars are driven by radiation pressure on dust rather than by magnetic activity as in the sun. The magnetic field results from one of the following. (1) Locally (but not globally) strong magnetic field spots. (2) A magnetically active main sequence companion. (3) An accretion disk around a companion, which amplifies the magnetic field of the accreted gas.

3.2. The role of magnetic fields

Models where magnetic fields play a role in shaping the circumstellar matter are of four kinds. (1) Magnetic fields deflect the flow close to the stellar surface, i.e., the magnetic pressure and/or tension are dynamically important already on the AGB (or post-AGB) stellar surface (e.g., Pascoli 1997; Matt et al. 2000; Blackman et al. 2001). (2) The magnetic field is weak close to the stellar surface. It plays a dynamical role only at large distances from the AGB star (e.g., Chevalier & Luo 1994; García-Segura 1997; García-Segura et al. 1999). (3) Locally enhanced magnetic fields on the AGB stellar surface form cool spots. Dust formation rate, hence mass loss rate, is enhanced above these cool spots (Soker & Zoabi 2002, and references therein). Magnetic fields never become dynamically important on a large scale. This mechanism can operate even for very slowly rotating AGB envelopes; spin-up by planets is enough to account for the required rotation velocity. This process may lead to the formation of moderate elliptical PNs (those with small departure from sphericity), but can't account for lobes, jets, etc. (4) Magnetic fields play a dominant role in the launching of jets from accretion disks, either around stellar companions or around the central star.

My view that the first two processes mentioned above (for more on these see García-Segura, Lopez, & Franco 2004; Matt, Frank, & Blackman 2004; Blackman 2004) can't work in shaping PNs was presented in several papers (e.g., Soker & Zoabi 2002). In particular, they require that the progenitor AGB (or post-AGB) envelope be spun-up by a stellar companion. The companion then has other effects on the mass loss process which are more influential. It is important to emphasize that any model based on magnetic activity must state the required angular velocity and/or angular momentum, and then the source of this angular momentum. Models for magnetic activity during the post-AGB phase, have in addition the problem of explaining the bipolar outflow from systems where the progenitor is still an AGB star.

Process (4) is of a different nature. From young stellar objects, active galactic nuclei, and many other systems, it is well established that accretion disks can form two jets. The question regarding the exact mechanism for launching the two jets is an open one. However, for the pure question of PNs shaping, the main issue is whether an accretion disk is formed or not; understanding the exact launching mechanism will not solve the major open questions regarding the shaping of PNs.

In light of the problems mentioned in this subsection (and which are discussed in more detail in some of my earlier papers cited above), I have the feeling that the APN3-meeting talks devoted to magnetic activity were much too optimistic in estimating their ability to shape PNs.

4. Post-AGB Envelope Instabilities

4.1. Personal note

The evolution of a single star during the final AGB phase (as it is about to leave the AGB) and early post-AGB phase holds some unsolved puzzles (even before adding the complications due to a binary companion). Some of these will be mentioned later in this section. My view is that present numerical codes can't handle all these complications, which involve processes on timescales and lengthscales which span a large domain, e.g., pulsations with large amplitudes on the surface, possible magnetic activity with local dust formation close to the surface, large convective eddies, long-term envelope relaxation (see later this section). In several papers, and in this section, I address some of these issues. Two recent papers (Soker 2003c; Soker & Harpaz 2003) were rejected by journals following referee reports. I think the arguments in these papers still hold, even if containing some speculative components. I have very strong criticisms on these referee reports, but I will not present them for the following reason. My paper on the magnetic activity of the cool component in symbiotic systems (Soker 2002e) received a very negative referee report (it was published following a positive report by a second referee). I presented the entire report with my strong criticism at a meeting on symbiotic stars in 2002. I submitted these for the Proceedings of that meeting, but was asked by the editors to remove this report and my criticism from the Proceedings. In the near future, therefore, I will not repeat such an attempt (it is not a common practice in our community). I think that the present situation, where someone can present his or her scientific view (i.e., in a referee report) without the need to stand behind this view (because it is not going to be published anywhere) is scientifically intolerable. The electronic publication system must be used to change the refereeing system. For example, a paper can be posted in a public place for a few weeks for open comments from anyone

interested. Should someone think that the paper should not be published, his or her view (with the name) can be given along with the paper, and with the authors' reply; future readers will make their own decision in the dispute.

4.2. Indications for long-term instabilities

The evelopes of upper AGB stars are known to be unstable, not only to oscillations on dynamical time scales of ~ 1 yr, but also to much longer time-scale perturbations. On the theoretical side there are several effects that may lead to such long-time scale variations. Icke, Frank, & Heske (1992) found chaos in the behavior of oscillating AGB stars on time-scales much longer than the dynamical time. Ya'ari & Tuchman (1996, 1999) emphasize the need to include long-term nonlinear thermal effects, which change the entropy structure of the envelope, when analyzing pulsating AGB stars. The dependence of the opacity on temperature, in particular in the temperature range appropriate for the photospheres of upper AGB stars, may also lead to sharp changes in the AGB stellar radius (Soker 2003c). This effect is particularly important in oxygen-rich AGB stars because the opacity sharply increases as temperature drops below ~ 2900 K, and it may lead to large expansion, a process termed opacity-induced over-expansion (Soker 2003c). This may occur, therefore, when the photospheric (effective) temperature drops to $T_p \sim 2900$ K. The much higher opacity implies a much lower photospheric density, which allows the envelope to expand (I will return to this effect later in this section). Finally, when the envelope mass becomes low the AGB star stops expanding and starts contracting (see below). The numerical stellar evolutionary model kindly given to me by Amos Harpaz (Soker 1992) shows the stellar envelope shrinking a little when the envelope mass becomes $M_{\rm env} \simeq 0.16 M_\odot$, and then expanding again when $M_{\rm env} \simeq 0.08 M_\odot$.

From the observational direction, Zijlstra, Bedding, & Mattei (2002) studied the long-term period evolution of the Mira variable R Hydrae. They find the orbital period to decrease from 495 days to 385 days in ~ 200 yr, from which they deduce a decrease of the stellar radius by $\sim 16\%$. They also argue for a strong decline in the mass loss rate, by a factor of ~ 10, with the envelope contraction. Zijlstra et al. (2002) then very nicely raise the possibility that if the behavior of R Hydrae is periodic, it can account for multiple semi-periodic concentric shells (arcs; rings; I term them 'M-arcs').

4.3. Motivation for long-term semi-periodic evolution

As indicated in the previous subsection, there are strong arguments in favor of long-term semi-periodic variations in upper-AGB stars. I now show that such behavior may resolve some puzzling issues.

(1) M-arcs. Zijlstra et al. (2002) already proposed that long-term non-linear behavior like that in R Hydrae can form M-arcs. Presently there is a disagreement on the process that forms M-arcs. In the literature there are several proposed models: (*i*) Binary interaction. It seems that this model can't work (see Soker 2002b). (*ii*) Instability in dust-disk coupling (Deguchi 1997; Simis, Icke, & Dominik 2001; Meijerink, Mellema, & Simis 2003). Although this model is popular, I think it has some problems (Soker 2002b). (*iii*) Solar-like magnetic activity cycle (Soker 2000; García-Segura, Lopez, & Franco 2001). As more PNs are found to have M-arcs (Corradi et al. 2004), this speculative idea becomes less likely. (*iv*) Van Horn et al. (2003) propose that the influence of mass loss on the H-burning shell can set long-term semi-periodicity in the nuclear burning rate and mass loss rate. A crucial assumption in their model is that the mass flux throughout the envelope is constant and equals the mass loss flux at the stellar surface. I consider this assumption unrealistic, as numerical models show the envelope mass decreasing (e.g., Soker 1992; Soker & Harpaz 1999[2]), rather than mass being supplied to the envelope by the core. It seems the nuclear burning rate will not be influenced by the mass loss process. (*v*) Long-term envelope instabilities (Zijlstra et al. 2002). In the next subsection I will propose a phenomenological model for such a behavior. In any case, it seems that the mass-losing star blows the M-arcs before being disturbed. Therefore, I speculate that most PNs with M-arcs come from binary interation type 3 of section 2, i.e., the companion does not disturbed much the AGB star, and shaping occurs mainly via accretion and jet blown by the companion. Type-4 interacting binaries can also lead to M-arcs if the interaction occurs at a late stage. The images of most PNs with M-arcs (Corradi et al. 2004) look like spherical shells that were shaped by jets, and most don't have large bubbles and narrow waist. Large bubbles and narrow waist are likely to reuslt from strong interaction (Soker & Rappaport 2000) that may prevent spherical M-arcs

(2) Mass loss rate and transition time. AGB stars start to shrink and their effective temperature starts to increase when their envelope mass decreases to $M_{\rm env} \simeq 0.2 - 0.8 M_\odot$, with the higher values for more massive cores. In many models for dust formation (e.g., Wachter et al. 2002), the mass loss rate steeply decreases as the temperature increases. The strong dependence on the temperature implies that as the star evolves along the post-AGB

[2]Note that the density scale in Figs. 1-5 of Soker & Harpaz (1999) is too low by a factor of 10; the correct scale is displayed in their Fig. 6.

track and becomes hotter, at constant luminosity, the mass loss rate steeply decreases with time. However, observations of planetary nebulae (PNs) and stellar evolution calculations along the post-AGB require the high mass loss rate to continue during the early post-AGB phase (e.g., Tylenda & Stasinska 1994). Models where the stellar effective temperature is the sole main physical parameter which determines the mass loss rate, therefore, predict too long post-AGB evolution (for more on this see Soker & Harpaz 2003). Soker & Harpaz (2003) argue that the envelope structure, in particular the entropy and density gradients, should be among the main parameters which determine the mass loss rate on the tip of the AGB and the early post-AGB evolutionary phases. The entropy profile becomes steeper and the density profile becomes shallower as the star becomes hotter on the early post-AGB phase, until the star heats up to $T \gtrsim 8000$ K. Soker & Harpaz (2003) propose that mass loss rate stays very high because of the envelope structure, and drops only when the effects of the temperature become important once again as the post-AGB star heats up to $\sim 6,000$ K. Note, they do not propose a new mass loss mechanism, but rather mention several mechanisms by which these profiles may influence the mass loss rate within the popular mechanism for mass loss on the AGB, where pulsations coupled with radiation pressure on dust cause the high mass loss rate (e.g., Höfner 1999; Winters et al. 2000; Andersen, Höfner & Gautschy-Loidl 2003; Willson 2004). This discussion suggests that some effect(s) in addition to the dependence on effective temperature (or stellar radius and luminosity) must operate during the upper AGB phase. Long-term semi-periodic oscillations, resulting from the steep entropy profile and shallow density profile, are discussed in the next subsection.

4.4. Phenomenological treatment of long-term oscillations

When the envelope mass of an AGB star declines to $\lesssim 0.2 M_\odot$ the density profile becomes very shallow and the entropy profile very steep as the envelope mass decreases (see graphs in Soker 1992, and Soker & Harpaz 1999). This can be seen from simple principles (Soker & Harpaz 1999, 2003; Soker 2003c, where the quantitative derivation is given). The photospheric density, derived from the definition of the optical depth being 2/3, is inversely proportional to the the photospheric temperature T_p, stellar radius R, and opacity κ: $\rho_p \propto (R^2 \kappa T_p)^{-1}$. As the star evolves along the AGB, the temperature drops and the opacity drops as well, increasing the photospheric density. Because of mass loss and increasing radius at the same time, the average density in the envelope decreases. The outcome is that the density profile in the envelope becomes very shallow. To maintain the convective energy flux in a low density envelope, the entropy profile becomes very steep (Soker & Harpaz 1999). The outcome is an envelope prone to instabilities. Since the photospheric density must be lower than the average envelope density, the envelope must eventually shrink to increase the

average envelope density and lower the photospheric density. This is the reason AGB stars start to shrink and heat up when their envelope still contains substantial mass. For a core mass of $M_c \simeq 0.6 M_\odot$ the AGB star starts shrinking when $M_{\rm env} \simeq 0.2 M_\odot$ (for $M_c \simeq 0.9$ the AGB star starts shrinking earlier, when $M_{\rm env} \simeq 0.8 M_\odot$; see data in Frankowski 2003). Using the data given by Frankowski (2003; also private communication), and Soker (1992), I take a simple formula to describe the equilibrium, i.e., non-oscillatory, average stellar radius as a function of envelope mass in the range $0.02 < M_{\rm env} < 0.2 M_\odot$. I take

$$R_{\rm eq} = 260 + 1400 M_{\rm env} - 3500 M_{\rm env}^2, \tag{1}$$

where envelope mass is in units of solar mass and radius in units of solar radius. This function is drawn as a thick line on the upper panel of Figure 1.

The shallow density profile has the following implication when mass loss rate is high. To maintain a constant stellar radius the lost mass must be replaced by mass from inner layers. Because the envelope density profile is shallow, to maintain a negative density profile, mass must flow outward from deep layers. This process increases the gravitational energy of the envelope; the source of this energy is the nuclear burning, i.e., the stellar luminosity. Because the envelope stays in a quasi-equilibrium, only a small fraction, η, of the stellar luminosity, $L_{\rm eq}$, will be used to lift mass. Let me take a high mass loss rate of $\sim 10^{-4} M_\odot~{\rm yr}^{-1}$, such that in ~ 10 yr a mass of $\Delta m \simeq 10^{-3} M_\odot$ is lost. (For an AGB star with $L_{\rm eq} = 6000 L_\odot$ the maximum mass loss rate will be lower by a factor of 3-5, compared with the scaling used here.) I also scale the equation with $\eta = 10^{-3}$, $L_{\rm eq} = 6000 L_\odot$, and a core mass of $M_c = 0.6 M_\odot$. To lift mass from an average radius of $r_{\rm in} \sim 0.1 R_{\rm eq} \sim 30 R_\odot$ to large radii, the thermal time scale is

$$\tau \simeq \frac{G M_c \Delta m}{r_{\rm in} \eta L} \simeq 100 \left(\frac{\Delta m}{0.001 M_\odot} \right) \left(\frac{r_{\rm in}}{30 R_\odot} \right)^{-1} \left(\frac{\eta L_{\rm eq}}{6 L_\odot} \right)^{-1} ~{\rm yr}. \tag{2}$$

To summarize the previous paragraph, I propose that the shallow density profile on the upper AGB and early post-AGB phases implies that the envelope shrinks after a short period of high mass loss rate. After a time-scale of ~ 100 yr, which is basically a thermal time-scale, the envelope re-expands. Because of the steep entropy profile the envelope is prone to instabilities, and it rebounds to larger than the equilibrium radius. For demonstrative purposes only, I build the following qualitative phenomenological model. I take the envelope to possess long-term oscillations, as depicted by the thin line in the upper panel of figure 1. The exact form of the assumed long-term oscillation is not important for the present demonstration. In any case, the form used is given by

$$R_{long} = R_{\rm eq} + A_r, \tag{3}$$

where

$$A_r = -0.2 R_{\rm eq} \sin^2[2\pi(0.2 - M_{\rm env})/0.02] \qquad \text{for} \qquad \sin[2\pi(0.2 - M_{\rm env})/0.02] \leq 0 \tag{4}$$

and

$$A_r = 0.25(440 - R_{\rm eq}) \sin^{1/2}[2\pi(0.2 - M_{\rm env})/0.02] \qquad \text{for} \qquad \sin[2\pi(0.2 - M_{\rm env})/0.02] > 0. \tag{5}$$

Masses and radii are in solar units.

To follow the evolution with time, a mass loss formula should be given. Again, for demonstrative purposes I use a formula that includes very strong dependence on the temperature (or stellar radius), as found by people studying pulsations and dust formation (e.g., Bowen & Willson 1991; Höfner & Dorfi 1997; Wachter et al. 2002), but includes dependence on envelope mass as well, for reasons discussed in the previous subsection (Soker & Harpaz 2003). The mass loss rate is taken to be

$$\dot{M} = 10^{-4} \left(\frac{R}{400 R_\odot} \right)^8 \left(\frac{M_{\rm env}}{0.2 M_\odot} \right)^{-1.5} M_\odot ~{\rm yr}^{-1} \tag{6}$$

Although the numerical values in this formula were chosen to accord with the formula for $R_{\rm long}$, I suggest that its form is more general. With the mass loss rate as a function of envelope mass and radius given, the equations for the evolution of the envelope with time can be numerically integrated. The evolution of the mass loss rate with time is given by the lower line in the lower panel of Figure 1. The upper line in this panel gives the effective temperature, assuming a constant luminosity of $L_{\rm eq} = 6000 L_\odot$. As in the rest of this section, the dynamical oscillations (the regular Mira, etc., oscillations) on a time-scale of ~ 1 yr, are not considered.

Although very speculative, I hope that the postulated long-term oscillations discussed here will motivate more research into the post-AGB mass loss process. As indicated in section 2, the very high mass loss rate, which probably comes with a slower wind, may substantially increase the likelihood of disk formation, hence jets, around a companion. Finally, it is also possible that such long-term oscillations require the envelope to be perturbed, e.g., by being spun-up via tidal interaction with a companion. In such a case, only systems where the companion is close, but

not too close to prevent RLOF, will have strong long-term oscillations.

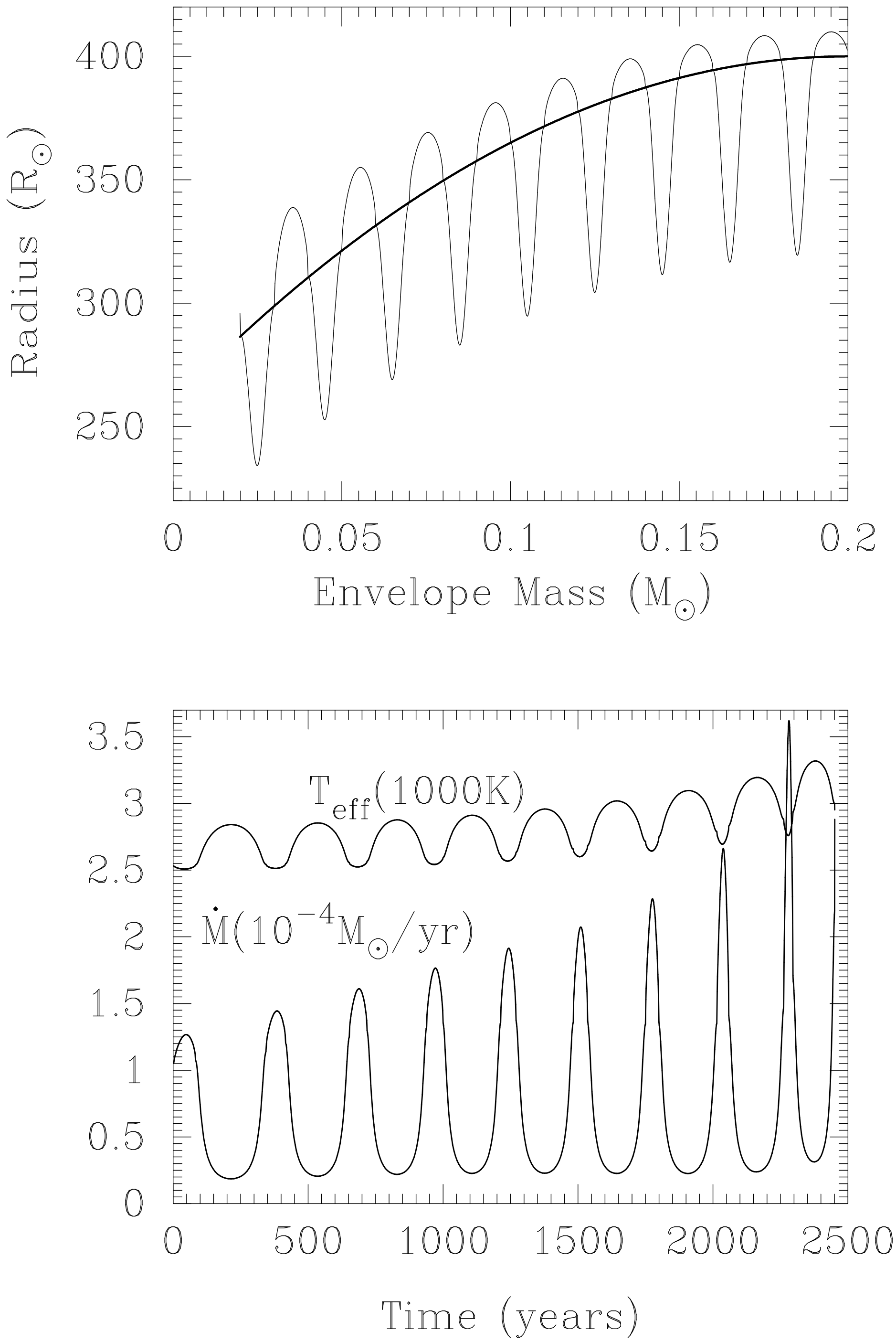

Fig. 1.— The phenomenological upper-AGB to post-AGB evolution. The upper panel shows the assumed variation of the envelope radius with envelope mass. The thick line is a crude fit to the average equilibrium radius of several AGB evolutionary models, while the thin line is the phenomenological postulated variation. The lower panel shows the calculated time evolution of the stellar effective temperature (for a stellar luminosity of $L_{\rm eq} = 6000 L_\odot$), and the mass loss rate. The calculation ends when the envelope mass decreases to $0.02 M_\odot$. Note than in the upper panel the star moves to the left during its evolution.

5. Bubbles in PNs and Clusters of Galaxies

This section summarizes the main results of three of my recent papers (Soker 2003a,b,d). These papers point to an interesting and nontrivial similarity in the morphology and some non-dimensional quantities between pairs of X-ray-deficient bubbles in clusters of galaxies and pairs of optical-deficient bubbles in PNs. This similarity leads me to postulate a similar formation mechanism, hence strengthening models for PN shaping by jets (not all PNs are shaped by jets). The presence of dense material in the equatorial plane observed in the two classes of bubbles constrains the jets and CFW activity in PNs to occur while the AGB star still blows its dense wind, or very shortly after. Only stellar companions can account for such jets. I then find that to inflate fat bubbles, the opening angle of the jets must be large, i.e., the half opening angle measured from the symmetry axis of the jets should typically be $\alpha \gtrsim 40^\circ$, or the jets should precess. For such wide-opening angle jets a collimated fast wind (CFW) is a more appropriate term. Narrow jets will form elongated lobes rather than fat bubbles. I emphasize the need to include jets with a large opening angle, i.e., $\alpha \simeq 30 - 70^\circ$, in simulating bubble inflation in both PNs and clusters of galaxies (these may resemble precessing jets, which are more difficult to simulate).

Most, or all, pairs of bubbles in clusters are found in cooling flow clusters, i.e., those where the radiative cooling time of the gas at their center is shorter than the age of the cluster. I find the term cooling flow appropriate. Gas cools radiatively, and star formation and AGN activity indicate that some gas is removed from the intracluster medium (ICM). Therefore, some inflow must exist, whether of the hot, warm, or cold medium. The cooling rate is much below values cited a decade ago; an appropriate term is therefore a *moderate cooling flow model* (Soker et al. 2001).

5.1. General arguments for jets in PNs

The idea that jets (or CFW) shape PNs is not new. Jet shaping was proposed by several authors to explain different morphological features, e.g., jets (or CFW) blown by a stellar companion (Morris 1987; Soker & Rappaport 2000) to explain bipolar PNs, and jets blown at the final AGB phase or early post-AGB phase to form dense blobs along the symmetry axis (Soker 1990; these blobs are termed ansae, or FLIERs for fast low ionization emission regions), or shape the PN (Sahai & Trauger 1998; Sahai 2004). Basically, the need for jet shaping came with the failure of the interacting stellar winds (ISW) model to explain some structures observed in PNs. (In the ISW model the shaping is due mainly to the interaction of the fast wind blown by the central star with a previously ejected non-spherical AGB wind; see Balick & Frank 2002 and references therein.) This failure was pointed out already

in 1990, when I showed that the ISW can't form ansae (Soker 1990). Later, the point-symmetric structure observed in many PNs (Sahai & Trauger 1998) finally killed the ISW model as the major PN shaping process. Wind interaction still occurs and influences the structure of PNs, but in most PNs it is not the major shaping process. Therefore, despite the optimistic view presented by Icke (see Rijkhorst, Icke, & Mellema 2004) in the last APN3 meeting when presenting his numerical simulations, I disagree with his claim that the ISW model can account for the shaping of PNs. The right direction to take to understand the shapes of bipolar PNs (those with large lobes or bubbles) is to simulate AGB winds blown simultaneously with jets (or CFW) blown by a companion (Garcia-Arredondo & Frank 2004), as proposed by Morris (1987) and Soker & Rappaport (2000). On the observational side, a search for CFW seems to be promising (e.g., Lee, Lim, & Kwok 2004).

Despite these arguments, and unlike the dominant view in the clusters community, the idea of shaping by jets is controversial in the PNs community. I think that the similarities in the structure of pairs of bubbles in clusters and in some PNs strongly support jets' shaping of bubbles and lobes in PNs. Note that not all PNs have bubbles (the more spherical cavities) or lobes (the more elongated cavities), so not all PNs are shaped by jets.

5.2. The similarities

Chandra X-ray observations of clusters of galaxies reveal the presence of X-ray-deficient bubbles in the inner regions of many clusters, e.g., Hydra A (McNamara et al. 2000), Abell 2052, (Blanton et al. 2001, 2003), A 2597 (McNamara et al. 2001), RBS797 (Schindler et al. 2001), Abell 496 (Dupke & White 2001), and Abell 4059 (Heinz et al. 2002). These bubbles are characterized by low X-ray emissivity, implying low density. In most cases, the bubbles are sites of strong radio emission. The optical morphologies of some PNs reveal pairs of bubbles (cavities), similar in morphology to the pairs of X-ray-deficient bubbles in clusters of galaxies. Examples are given in table 1, and a more detailed discussion, including more examples, are in Soker (2003a).

Despite the several orders of magnitude differences in some quantities between clusters and PNs, the values of some non-dimensional quantities are similar (see table 2 of Soker 2003a). The main qualitative difference between the two classes is the environment into which the bubbles expand. Bubbles in clusters evolve inside the ICM, which is in hydrostatic equilibrium; if global flow is present, it is highly subsonic. The bubbles in clusters move outward because of buoyancy. In PNs the bubbles move outward as part of the global outflow of the wind. Gravity is negligible in PNs. However, this difference doesn't influence the inflation phase of the bubbles.

The main relevant similarities between the two types of bubble pairs are as follows. (1) The most striking similarity is in the morphology. In particular, in many cases there is a dense region in the equatorial plane between the two bubbles, e.g., the cluster A 2597 (McNamara et al. 2001) and the Owl PN(NGC 3587: Guerrero et al. 2003). (2) In some cases more than one pair of bubbles are seen, e.g., in the Perseus cluster (Fabian et al. 2000, 2002) and in the PN Hu 2-1 (Miranda et al. 2001b). (3) In both types of bubbles the density inside the bubble is 2-3 orders of magnitude lower than that in the environment, with an opposite ratio in temperatures. (4) In both cases the typical lifetime of observed bubbles is estimated to be ~ 10 times the estimated duration of the main energy injection phase that forms the bubbles. (5) In clusters the bubbles move subsonically, or mildly supersonically, through the ICM. In PNs the situation is more complicated, but this does not much influence the inflation phase of the bubbles (see Soker 2003a for more on these).

It is those similarities in morphologies and some non-dimensional quantities that hint at a similar formation process in these vastly different objects (clusters and PNs). In clusters it is commonly accepted that pairs of bubbles are formed by two opposite jets (e.g., Brighenti & Mathews 2002; Brüggen 2003; Brüggen et al. 2002; Fabian et al. 2002; Nulsen et al. 2002; Quilis, Bower, & Balogh 2001; Soker, Blanton, & Sarazin 2002; Omma et al. 2003). An axisymmetrical density structure of the ambient medium is not needed to form the cluster's bubbles (only very close to the AGN, on a scale much smaller than the bubble size, does the accretion disk influence the flow).

The similarity in several non-dimensional quantities suggests that if the initial flow structure is similar, the bubble morphologies will be similar, as observed. This leads to the following. (1) The similar shapes strengthen the general idea that jets (or CFW) form and shape the bubbles in PNs, as well as other types of bipolar PNs.

(2) The low density in the bubble implies that the jets are fast, with a speed of $>$ 100 km s^{-1} in PNs. Therefore, the object launching the jets in PNs must be compact, since the jets' speed is of the order of the escape velocity (Livio 2000). (3) The presence of more than one pair of bubbles in the PN Hu 2-1 indicates, as in clusters, multiple episodic events. (4) In clusters the surrounding density increases as radius decreases down to the center. The similar bubble morphologies and the presence of dense material in the equatorial plane between the two bubbles suggests that a similar ambient medium exists in PNs when the jets are blown. Namely, the AGB dense wind is still active, or has ceased only recently, when the jets are blown in PNs. This is possible only if the jets are blown by a companion, or the central star moves extremely rapidly from the AGB to become a compact star that can blow fast jets. This rapid evolution is in contrast to finding of stellar evolution studies, and is also unlikely to explain the multiple activity (point 3 above; Miranda et al. 2001b argue for

a CFW that was blown by a binary system progenitor of Hu 2-1). One of the observational implications is that we should see evidence of fast jets in objects that are still unambiguous AGB stars. A good example is the system OH231.8+4.2 (Rotten Egg nebula), for which Kastner et al. (1998) detect the presence of a Mira inside this bipolar nebula which contains jets (Zijlstra et al. 2001). Zijlstra et al. (2001) present evidence for jets in some OH/IR early post-AGB stars. There are also resolved jets near some AGB stars (e.g., Imai et al. 2002, 2003, for W34A; Hirano et al. 2004 and Sahai et al. 2003 for V Hydrae; Vinkovic et al. 2004).

5.3. Summary: main results of the similar morphology

The similarity in morphology and some other properties strongly supports jets or CFW models for the shaping of pair of bubbles in PNs. The presence of dense material in the equatorial plane constrains the jets and CFW activity to occur while the AGB star still blows its dense wind, or very shortly after. The requirement that the jets and CFW be fast and the presence of more than one pair of bubbles in, e.g., Hu 2-1, constrains the object that blows the jets and CFW to be a compact companion, i.e., a main sequence or a white dwarf star. Although I considered here only PNs with well defined pairs of closed bubbles, the results are more general in strengthening the idea that bipolar and extreme elliptical PNs are shaped by jets or CFW blown by an accreting companion. Going from PNs to clusters, some determined quantities in PNs, e.g., the inflating jets are non-relativistic, may help constrain the bubble formation process in clusters.

Comments to table 1: The images of all these objects are summarized in a *powerpoint* file I presented during the APN3 meeting (2003). The site:
http://www.astro.washington.edu/balick/APN/APN_talks_posters.html
(go the 'ppt' file in the "discussion" of session 13).

Free access to individual images are at these sites:
[1] http://arxiv.org/PS_cache/astro-ph/pdf/0210/0210054.pdf
[2] http://ad.usno.navy.mil/pne/images/rob22.jpg (Terzian & Hajian 2000)
[3] http://arxiv.org/PS_cache/astro-ph/pdf/0007/0007456.pdf
[4] http://arxiv.org/PS_cache/astro-ph/pdf/0303/0303056.pdf
[5] http://arxiv.org/PS_cache/astro-ph/pdf/0107/0107221.pdf
[6] http://ad.usno.navy.mil/pne/images/vv171.jpg
[7] http://arxiv.org/PS_cache/astro-ph/pdf/0010/0010450.pdf
[8] http://ad.usno.navy.mil/pne/images/he2_104.jpg
[9] http://chandra.harvard.edu/photo/cycle1/hcg62/index.html

Table 1. Similar images of PNs and clusters

Structure	Clusters	PNs
Butterfly shape of the bright region; faint along symmetry axis	Abell 478 (Sun et al. 2003, fig 1) [1]	Roberts 22 (Sahai et al. 1999, fig. 1a) [2]
Pairs of fat spherical bubbles near center	Perseus (Fabian et al. 2000) [3]	NGC 3587 (Guerrero et al. 2003, fig. 1) [4]
Closed bubbles connected at the equatorial plane	Abell 2052 (Blanton et al. 2001, fig. 3) [5]	VV 171 (Sahai 2001) [6]
Open bubbles connected at the equatorial plane	M 84 (Finoguenov & Jones 2001, fig 1) [7]	He 2-104 (Sahai & Trauger, 1998) [8]
Pair of bubbles detached from a bright center	HCG 62 (Vrtilek et al. 2002) [9]	Hu 2-1 (Miranda et al. 2001b, fig. 2) [10]
Point-symmetric elongated lobes	Hydra A (McNamara et al. 2000, fig. 1) [11]	NGC 6537 (Balick 2000, fig. 2) [12]
Pairs of bright bullets along the symmetry axis	Cygnus A (Smith et al. 2002, fig. 1) [13]	NGC 7009 (Balick et al. 1998, fig. 1,4) [14]

Note. — Similar images of bubbles in clusters of galaxies and planetary nebulae (PNs). In clusters these are X-ray images (e.g., with X-ray deficient bubbles), while in PNs they are optical images (e.g., with optical deficient bubbles). In the first five pairs of images the similarity is of high degree. In the last two pairs of images the similarity between the cluster and the PN is less.

[10a] http://arxiv.org/PS_cache/astro-ph/pdf/0009/0009396.pdf
also: [10b] http://ad.usno.navy.mil/pne/images/hu21_ha.gif
[11] http://arxiv.org/PS_cache/astro-ph/pdf/0001/0001402.pdf
[12] http://ad.usno.navy.mil/pne/images/ngc6537.jpg
[13] http://arxiv.org/PS_cache/astro-ph/ps/0109/0109488.f1.gif
[14a] http://ad.usno.navy.mil/pne/images/ngc7009.jpg
see also (Goncalves et al. 2003, fig. 1)
[14b] http://arxiv.org/PS_cache/astro-ph/pdf/0307/0307265.pdf

6. Relevant Related Objects

The main point of this review, like that of many of my papers in the last 15 years, is that binary interaction, with a stellar or a substellar companion (planets or brown dwarfs), can account for the shaping of PNs. PN research can contribute a lot to the study of shaping of some other astrophysical systems, and at the same time benefit from research conducted to understand these and other objects. In this section I list some of these objects.

Symbiotic Systems. Schwarz gave a talk (Schwarz & Monteiro 2004) and Corradi (2004) led a discussion on the relation of symbiotic systems to bipolar PNs−those with lobes (or fat-bubbles) and an equatorial waist between them. Although the relation of PNs to symbiotic systems was noted by several people in the past, Corradi and Schwarz (1995, and other papers) led the research along this line. The morphological similarity between some symbiotic nebulae and some bipolar PNs strongly suggests that bipolar PNs are formed by binary systems, most with the accreting companion outside the AGB envelope. The accumulating evidances for jets in symbiotic systems (Kellogg, Pedelty, & Lyon 2001; Brocksopp et al. 2003) add to their connection to PNs and some other objects listed here. For example, note the similarity in the X-ray jet in R Aqr (Kellog et al. 2001) and the X-ray jet in Mz 3 (Kastner et al. 2003). Other arguments for binary progenitor models of bipolar PNs, such as the class of post-AGB stars with a companion and a circumbinary disk (Jura 2004; Van Winckel 2003, 2004), are summarized in Soker (1998).

Supersoft X-ray Sources. Supersoft X-ray sources are thought to be white dwarfs accreting at rates of $10^{-8} - 10^{-7} M_{\odot}$ yr^{-1} from a companion, and sustaining nuclear burning on their surface (e.g., Greiner 1996). Fast, $\sim 1000 - 5000$ km s^{-1}, collimated outflows have been observed in some supersoft X-ray sources (Southwell, Livio, & Pringle 1997; Becker et al. 1998; Motch 1998). These systems teach us that accreting WDs can blow jets (Soker & Rappaport 2000). Bipolar PNs hint that bipolar nebulae should exist around some supersoft X-ray sources, even if very faint.

Novae. The relation of novae to PNs was reviewed by Bode (2004) at the APN3 meeting. After the novae eruption, the system enters a short common envelope phase. The axisymmetrical structure of many novae eruptions shows that common envelope phase can lead to axisymmetrical structures. About 20 PNs are known, and many more are expected, to harbor close binary systems (Bond 2000; Sorensen & Pollacco 2004; Hillwig 2004; De Marco et al. 2004) which went through a common envelope phase.

R Coronae Borealis stars. These are carbon-rich hydrogen-poor stars, with effective temperatures more than twice those of AGB stars. They are known to form dust sporadically on local spots very close to the surface (at APN3 these objects were discussed by Clayton

2004). Their relevance is that they show that dust can be easily formed very close to the surface of giant stars, in a non-spherical configuration (Soker & Clayton 1999).

Young stellar objects. Many YSO are known to blow jets. Similar jets in PNs (Lee & Sahai 2004), e.g., similar outflow speeds, strengthen the case for an accretion disk as the source of the jets in PNs, and most likely indicate that the companion blowing the jet is a main-sequence companion. (Much faster jets are likely to originate at an accreting white dwarf, as in supersoft X-ray sources.)

Massive stars: WR 98A. This massive binary system, where one of the components is a massive WR star, has a circumbinary matter in a spiral structure (Monnier, Tuthill, & Danchi 1999). This spiral structure results from a binary interaction. Spiral structure is expected to be formed by some binary-systems progenitors of PNs (Soker 1994; Mastrodemos & Morris 1999). The spiral is expected to be smeared quite fast, in particular after ionization starts. WR 98A and similar systems suggest that careful observations of proto-PNs, possibly by dividing two images at different spectral lines, may reveal spiral structure.

Massive stars: η Car. Gehrz (2004) reviewed η Car at the APN3 meeting. This system which is known to harbor a binary system, shows that a binary system is behind the bipolar structure. The arguments given here, i.e., that the companion blows jets that form the lobes of bipolar PNs, suggest that in η Car as well the bipolar structure was formed by jets blown by the accreting companion (Soker 2001b)

Massive stars: SN 1987A. Sugerman & Crotts (2004) review the structure of the material around the progenitor of SN 1987A. The basic structure is similar to that of some bipolar PNs. This suggests, as was noted in the past, that a binary companion most likely shaped the circumstellar matter around SN 1987A, and that it accreted mass and blew jets.

Massive stars: ρ Cassiopeiae. This yellow hypergiant stars is known to go through non-periodic outbursts (Lobel et al. 2003). The outbursts are suggested to result from envelope instabilities (Lobel et al. 2003). This may be related to the postulated long-term oscillations of upper AGB stars, in showing that envelopes of giant stars may be unstable on time-scales of $10 - 1000$ yr, i.e., longer than the dynamical time.

Clusters of galaxies. These objects are different in nature from all other related objects listed above, as these are not stellar objects, and the length-scales involved are ~ 5 orders of magnitude larger than those involved in PNs. However, the similar structure of bubbles in clusters and bubbles in PNs is striking and nontrivial. I argue that the similarity in structure and several non-dimensional quantities (Soker 2003a) has implications for the formation mechanisms of fat-bubbles in PNs: they are formed by jets blown by a companion while the progenitor is still an AGB star, or a very young post-AGB star. In Soker (2003b) I argue

that some of the fat-bubbles in clusters and PNs are likely to be formed by jets having a wide opening angle (collimated fast wind; CFW), or precessing jets. Rayleigh-Taylor instability at shell's front is discussed in Soker (2003d).

Subdwarf B binaries. These objects are related to the question of the transition from spherical to axisymmetrical mass loss geometry just as the star is about to leave the AGB. In section 2 I explain this in the paradigm of stellar binary interaction. The subdwarf B binaries (sdB) composed of a helium core of mass $\sim 0.5 M_\odot$ and a very thin hydrogen layer of $< 0.02 M_\odot$, and a companion, either a main sequence star of a white dwarf, or even a brown dwarf companion (Rauch 2003), with orbital periods in the range ~ 1 hour-1000 days (see Morales-Rueda, Maxted, & Marsh 2003, and references therein). It is not clear how these stars (the helium core stars) lose most of their hydrogen-rich envelope on the red giant branch (RGB) but still managed to ignite helium (Morales-Rueda et al. 2003). It is probably that the binary interaction that causes most of the envelope to be lost occurs when these stars are on the upper RGB, and just about to ignite helium. The rapid interaction with stars on the upper RGB can be understood from the evolution of the stellar radius with core mass. The analytical approximate relations from Iben & Tutukov (1984) for RGB stars which are descendant of population I main sequence stars in the mass range $0.8 < M/M_\odot < 2.2$ read

$$\frac{R_g}{R_\odot} = 10^{3.5} \left(\frac{M_c}{M_\odot}\right)^4 \qquad \text{and} \qquad \dot{M}_c = 10^{-5.36} \left(\frac{M_c}{M_\odot}\right)^{6.6} M_\odot \ \mathrm{yr}^{-1}, \tag{7}$$

where M_c is the core mass, and R_g the RGB radius. These relations show that when the RGB star reaches large radii, its core mass is already large, and the evolution becomes more rapid as the core mass and radius increase. Considering that tidal interaction evolves on short time scales as well (section 2), it is expected that many RGB stars will interact with their binary companion during a short time when they are large and their core is massive. (These stars can then ignite helium in the core while cooling after envelope collapse; D'Cruz et al. 1996.) Similar rapid evolution of binary interaction occurs on the upper AGB. This is the relation of these binary stars to PNs and proto-PNs showing rapid transition from spherical to axisymmetrical mass loss.

This review was initiated by two meetings I attended in the summer of 2003: The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies, and Asymmetrical Planetary Nebulae III. I benefited from discussions with many people during these two meetings. Among these are James Binney, Adam Frankowski, Joel Kastner, Raghvendra Sahai, Hans Van Winckel, Jan Vrtilek, Ray White, and Albert Zijlstra. Special thanks to my long-time collaborator Amos Harpaz, for making possible the study of the AGB and post-AGB stellar evolution, and for many useful discussions. This research was supported in part by the Israel Science Foundation.

REFERENCES

Andersen, A. C., Höfner, S., & Gautschy-Loidl, R. 2003, A&A, 400, 981

Balick, B. 2000, "Asymmetrical Planetary Nebulae II: From Origins to Microstructures," eds. J.H. Kastner, N. Soker, &

S. Rappaport, ASP Conf. Ser. Vol. 199, p. 41

Balick, B., Alexander, J., Hajian, A. R., Terzian, Y., Perinotto, M., & Patriarchi, P. 1998, AJ, 116, 360

Balick, B., & Frank, A. 2002, ARA&A, 40, 439

Becker, C. M. Remillard, R. A. Rappaport, S. & McClintock J. E. 1998, ApJ, 506, 880

Blackman, E. G. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0309752)

Blackman, E. G., Frank, A., Markiel, J. A., Thomas, J. H., & Van Horn, H. M. 2001, Nature, 409, 485

Blanton, E. L., Sarazin, C. L., McNamara, B. R., & Wise, M. W. 2001, ApJ, 558, L15 (astro-ph/0107221)

Blanton, E. L., Sarazin, C. L., & McNamara, B. R. 2003, ApJ, 585, 227

Bobrowsky, M. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Bode, M. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310068)

Bond, H. 2000, ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport (San Francisco:ASP), 115

Bowen, G. H., & Willson, L. A. 1991, ApJ, 375, L53

Brighenti, F., & Mathews, W. G. 2002, ApJ, 574, L11

Brocksopp, C., Sokoloski, J. L., Kaiser, C., Richards, A. M., Muxlow, T. W. B., & Seymour, N. 2003, MNRAS, in press (astro-ph/0309384)

Brüggen, M. 2003, (astro-ph/0301352)

Brüggen, M., Kaiser, C. R., Churazov, E., & Ensslin, T. A. 2002, MNRAS, 331, 545

Chevalier, R. A., & Luo, D. 1994, ApJ, 421, 225

Clayton, G. C. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Corradi, R.Ł. M. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Corradi, R.Ł. M. & Schwarz, H. E. 1995, A&A, 293, 871

Corradi, R.Ł. M. Sanchez-Blazquez, P. Mellema, G. Gianmanco, C. & Schwarz, H. E. 2004, A&A, submitted

D'Cruz, N. L., Dorman, B., Rood, R. T., & O'Connell, R. W. 1996, ApJ, 466, 359.

Deguchi, S. 1997, in Planetary Nebulae, IAU Symp. 180, eds. H. J. Habing & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 151

De Marco, O. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310108)

De Marco, O., Bond, H. E., Harmer, D., & Fleming, A. J. 2004, submitted

Dorch, S. B. F., & Freytag, B. 2002, in Modeling of Stellar Atmospheres, IAU Sym., eds., N. E. Piskunov, W. W. Weiss, and D. F. Gray, (astro-ph/0208523)

Dupke, R., & White, R. E. III 2001, High Energy Universe at Sharp Focus: Chandra Science, ed. E. M. Schlegel & S. Vrtilek (San Francisco: ASP Conference Series), 51

Elitzur, M., Ivezic, Z., & Vinkovic, D. 2002, in Workshop on Mass-Losing Pulsating Stars and Their Circumstellar Matter, in press (astro-ph/0207513)

Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., & Perley, R. A. 2002, MNRAS, 331, 369

Fabian, A. C., et al. 2000, MNRAS, 318, L65 (astro-ph/0007456)

Finoguenov, A., & Jones, C. 2001, ApJ, 547, L107 (astro-ph/0010450)

Frankowski, A. 2003, A&A, 406, 265

Garica-Arredondo, F. & Frank, A. 2004, preprint (astro-ph/0307454)

García-Segura, G. 1997, ApJ, 489, L189

García-Segura, G. Lopez, J. A. & Franco, J. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

García-Segura, G., Langer, N., Rozyczka, M., & Franco, J. 1999, ApJ, 517, 767

García-Segura, G. Lopez, J. A. & Franco, J. 2001, ApJ, 560, 928

Gehrz, R. D. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Goncalves, D. R., Corradi, R. L. M., Mampaso, A., & Perinotto, M. 2003, ApJ, in press (astro-ph/0307265)

Greiner, J. ed. 1996, Lecture Notes in Physics 472, Supersoft X-Ray Sources (Berlin: Springer)

Guerrero, M. A., Chu, Y.-H., Manchado, A., Kwitter, K. B. 2003, AJ, 125, 3213 (astro-ph/0303056)

Heinz, S., Choi, Y.-Y., Reynolds, C. S., & Begelman, M. C. 2002, ApJ, 569, L79

Hillwig, T. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310043)

Hirano, N. Shinnaga, H. Zhao, J.-H. Young, K. Fong, D. & Dinh, V.-T. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Höfner, S. 1999, A&A., 346, L9

Höfner, S., & Dorfi, E. A. 1997, A&A, 319, 648

Hrivnak, B. J., Kwok, S., & Su, K. Y. L. 2001, AJ, 121, 2775

Huggins, P. J., Muthu, C., Bachiller, R., Forveille, T., & Cox, P. 2003, A&A, in press

Iben, I. Jr. & Tutukov, A. V. 1984, ApJSupp, 54, 335

Icke, V. Frank, A. & Heske, A. 1992, A&A, 258, 341

Imai, H., Obara, K., Diamond, P. J., Omodaka, T., & Sasao, T. 2002, Nature, 417, 829

Imai, H., Obara, K., Diamond, P. J., Omodaka, T., & Sasao, T. 2003, RMxAC, 15, 74

Indra, B. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Jura, M. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Kastner, J. H., Balick, B., Blackman, E. G., Frank, A., Soker, N., Vrtilek, S. D., & Li, Jingqiang 2003, ApJ, 591, L37

Kastner, J. H., Weintraub, D. A., Merrill, K. M., & Gatley, I. 1998, AJ, 116, 1412

Kellogg, E., Pedelty, J. A., & Lyon, R. G. 2001, ApJ, 563, L151

Kemball, A. J., & Diamond, P. J. 1997, ApJ, 481, L111

Kwok, S., Su, K. Y. L., & Stoesz, J. A. 2001, in Astrophysics and Space Science Library Vol. 265, Post-AGB Objects as a Phase of Stellar Evolution, ed. R. Szczerba & S.K.Gorny (Dordrecht: Kluwer), 115

Lee, C.-F., & Sahai, R. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Lee, T.-H., Lim, J. & Kwok, S. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310433)

Livio, M. 2000, in Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport, ASP Conference Series, Vol. 199, (San Francisco: ASP), 243

Lobel, A., Dupree, A. K., Stefanik, R. P., Torres, G., Israelian, G., Morrison, N., de Jager, C., Nieuwenhuijzen, H., Ilyin, I., & Musaev, F. 2003, ApJ, 583, 923

Mastrodemos, N. & Morris, M. 1999, ApJ, 523, 357

Matt, S., Frank, A., & Blackman, E. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0308548)

Matt, S., Balick, B., Winglee, R., & Goodson, A. 2000, ApJ, 545, 965

McNamara, B. R., et al. 2000, ApJ, 534, L135 (astro-ph/0001402)

McNamara, B. R., et al. 2001, ApJ, 562, L149

Meijerink, R. Mellema, G. & Simis, Y. 2003, A&A, 405, 1075

Miranda, L. F., Gomez, Y., Anglada, G., & Torrelles, J. M. 2001a, Nature, 414, 284

Miranda, L. F., Torrelles, J. M., Guerrero, M. A., Vazquez, R., & Gomez, Y. 2001b, MNRAS, 321, 487 (astro-ph/0009396)

Monnier, J. D. Tuthill, P. G. & Danchi, W. C. 1999, ApJ, 525, L97

Morales-Rueda, L. Maxted, P. F. L. & Marsh, T. R. 2003, astro-ph/0309088

Morris, M. 1987, PASP, 99, 1115

Motch, C. 1998, A&A, 338, L13

Nulsen, P. E. J., David, L. P., McNamara, B. R., Jones, C., Forman, W. R., & Wise, M. 2002, ApJ, 568, 163

Omma, H., Binney, J., Bryan, G., & Slyz, A. 2003 (astro-ph/0307471)

Pascoli, G. 1997, ApJ, 489, 946

Sorensen, P. & Pollacco, D. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Quilis, V., Bower, R., & Balogh, M. L. 2001, MNRAS, 328, 1019

Rauch, T. 2003. (astro-ph/0311558)

Rijkhorst, E.-J., Icke, V., & Mellema, G. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0311392)

Sahai, R. 2001, in Galactic Structure, Stars and the Interstellar Medium, Eds. Charles E. Woodward, Michael D. Bicay, and J. Michael Shull, ASP Conf. Ser. Vol. 231 (San Francisco: ASP), 528

Sahai, R. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Sahai, R., Morris, M., Knapp, G. R., Young, K., & Barnbaum, C. 2003, Nature, 426, 261

Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357

Sahai, R., Zijlstra, A., Bujarrabal, V., Te Lintel Hekkert, P. 1999, AJ, 117, 1408

Schindler, S., Castillo-Morales, A., De Filippis, E., Schwope, A., & Wambsganss, J. 2001, A&A 376, L27

Schwarz, H. E. & Monteiro, H. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310074)

Simis, Y. J. W. Icke, V. & Dominik, C. 2001, A&A, 371, 205

Smith, D. A.; Wilson, A. S., Arnaud, K. A., Terashima, Y., & Young, A. J. 2002, ApJ, 565 195 (astro-ph/0109488)

Soker, N. 1990, AJ, 99, 1869

Soker, N. 1992, ApJ, 389, 628

Soker, N. 1994, MNRAS, 270, 774

Soker, N. 1995, MNRAS, 274, 147

Soker, N. 1997, ApJS, 112, 487

Soker, N. 1998, ApJ, 496, 833

Soker, N. 2000, ApJ, 540, 436 (astro-ph/0001281)

Soker, N. 2001a, ApJ, 558, 157 (astro-ph/0102110)

Soker, N. 2001b, MNRAS, 325, 584 (astro-ph/0103033)

Soker, N. 2002a, A&A, 386, 885 (astro-ph/0105142)

Soker, N. 2002b, ApJ, 570, 369 (astro-ph/0110474)

Soker, N. 2002c, MNRAS, 330, 481 (astro-ph/0107554)

Soker, N. 2002d, MNRAS, 336, 826 (astro-ph/0204157)

Soker, N. 2002e, MNRAS, 337, 1038 (astro-ph/0204356)

Soker, N. 2003a, PASP, 115, 1296 (astro-ph/0306616)

Soker, N. 2003b, A&A, in press (astro-ph/0309095)

Soker, N. 2003c, accepted by astro-ph (astro-ph/0305142)

Soker, N. 2003d, "Bubbles in planetary nebulae and clusters of galaxies : instabilities at bubble' fronts", preprint, to be posted on astro-ph

Soker, N., Blanton, E. L., & Sarazin, C. L. 2002, ApJ, 573, 533 (astro-ph/0201325)

Soker, N. & Clayton, G. C. 1999, MNRAS,307, 993 (astro-ph/9812263)

Soker, N. & Harpaz, A. 1999, MNRAS, 310, 1158 (astro-ph/9907407)

Soker, N. & Harpaz, A. 2003, accepted by astro-ph (astro-ph/0210586)

Soker, N. & Kastner, J. H. 2003, ApJ, 592, 498 (astro-ph/0209236)

Soker, N. & Rappaport, S. 2000, ApJ, 538, 241 (astro-ph/9911140)

Soker, N., & Rappaport, S. 2001, ApJ, 557, 256 (astro-ph/0102202)

Soker, N., White, R. E. III, David, L. P., & McNamara, B. R. 2001, ApJ, 549, 832 (astro-ph/0009173)

Soker, N., & Zoabi, E. 2002, MNRAS, 329, 204 (astro-ph/0106301)

Southwell, K. A. Livio, M. & Pringle, J. E. 1997, ApJ, 478, L29

Su, K. Y. L. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Sugerman, B., & Crotts, A. P. S., 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Sun, M., Jones, C., Murray, S. S., Allen, S. W., Fabian, A. C., & Edge, A. C. 2003, ApJ, 587, 619 (astro-ph/0210054)

Terzian, Y., & Hajian, A. R. 2000, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, eds. J.H. Kastner, N. Soker, & S. Rappaport, ASP Conf. Ser. Vol. 199, p. 33 (see PNs images at: http://ad.usno.navy.mil/pne/gallery.html)

Tylenda, R., & Stasinska, G. 1994, A&A, 288, 897

Van Horn, H. M. Thomas, J. H. Frank, A. & Blackman, E. G. 2003, ApJ, 585, 983

Van Winckel, H. 2003, ARA&A, 41, 391

Van Winckel, H. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Vinkovic, D., Elitzur, M., Hofmann, K.-H., & Weigelt, G. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press (astro-ph/0310012)

Vlemmings, W. H. T., Diamond, P. J., & van Langevelde H. J. 2002, A&A, 394, 589

Vrtilek, J. M., Grego, L., David, L. P., Ponman, T. J., Forman, W., Jones, C., & Harris, D. E. 2002, APS, APRB, 17107

Wachter, A. Schröder, K.-P., Winters, J. M. Arndt, T. U. & Sedlmayr, E. 2002, A&A, 384, 452

Willson, L. A. 2004, in Asymmetrical Planetary Nebulae III, eds. M. Meixner, J. H. Kastner, N. Soker, & B. Balick, ASP Conf. Series, in press

Winters, J. M., Le Bertre, T., Jeong, K. S., Helling, Ch., & Sedlmayr, E. 2000, A&A, 361, 641

Ya'ari, A. & Tuchman, Y. 1996, ApJ, 456, 350

Ya'ari, A. & Tuchman, Y. 1999, ApJ, 514, L35

Yurchyshyn, V. B., Wang, H., Goode, P. R., & Deng, Y. 2001, ApJ, 563, 381

Zijlstra, A. A., Bedding, T. R. & Mattei, J. A. 2002, MNRAS, 334, 498

Zijlstra, A. A. Chapman, J. M. te Lintel Hekkert, P. Likkel, L. Comeron, F. Norris, R. P., Molster, F. J., & Cohen, R. J. 2001, MNRAS, 322 280

Zijlstra, A. A., te Lintel Hekkert, P., Pottasch, SṘ., Caswell, JL̇., Ratag, M. & Habing, H. J. 1989, A&A, 217, 157

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